

Radio Frequency (RF) Trap for Confinement of Antimatter Plasmas Using Rotating Wall Electric Fields

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Abstract

Perturbations associated with a rotating wall electric field enable the confinement of ions for periods approaching weeks. This steady state confinement is a result of a radio frequency manipulation of the ions. Using state-of-the-art techniques it is shown that radio frequency energy can produce useable manipulation of the ion cloud (matter or antimatter) for use in containment experiments. The current research focuses on the improvement of confinement systems capable of containing and transporting antimatter.

Purpose of the Paper

The purpose of this paper is twofold. First is to incorporate existing RF technologies used exclusively in the communication regime into magnetic trap applications. This is accomplished by combining current RF methodologies with new and innovative techniques to increase the overall storage capabilities. Long term storage systems are a key enabling technology for a range of antimatter applications, including, potentially, space propulsion applications.

Second is to develop new design and fabrication techniques for the basic handling and manipulation of antiprotons. This is accomplished by proper transmission of RF power throughout the antimatter trap system.

Significance of Study

The annihilation of antiprotons with protons (P-P⁺) represents the highest energy density of any known reaction in physics. The typical conversion from matter to energy for the P-P⁺ is 10^8 MJ/g, or 10 orders of magnitude above that of current chemical systems).

This energy density represents a very attractive energy storage means, with potential to significantly benefit NASA propulsion missions and is show graphically in Figure 1.

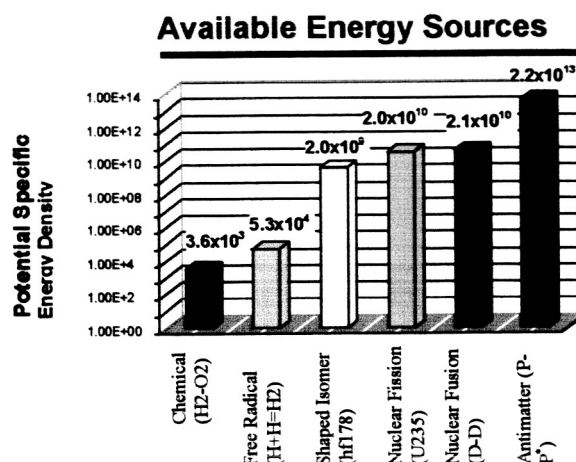


Figure 1. Available Energy Sources.

Summary

In this work, innovative and unique methods are developed and shown to overcome limitations of current state-of-the-art electromagnetic containment and manipulation of antimatter clouds. These methods include creation of new types of RF antennas that are capable of propagating an RF/microwave signal within the ion cloud. This unique subsystem was designed and developed using current Penning-Malmberg trap topologies as a model with significant modifications to allow the accurate transmission/reception of the RF signal.

With new results from this research incorporated into a Penning-Malmberg trap significant improvement in the control and manipulation of the antimatter cloud will be observed. This improvement is enough to have a large favorable impact on any system with a Penning-Malmberg trap using rotating electric fields.

History of the Penning-Malmberg Trap

The Penning-Malmberg trap concept has been in existence since the early 1980's. The trap incorporates static magnetic and DC electric fields along with an ultra-high vacuum (typically 10^{-11} Torr range or lower). Figure 2 shows schematically the classical Penning trap.

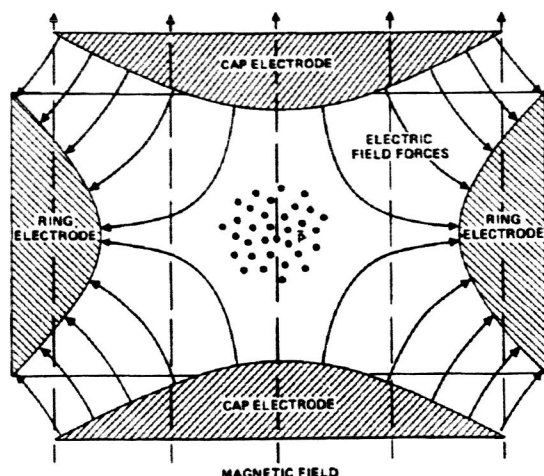


Figure 2. Classic Penning Trap.

The Penning Trap exhibits a hyperbolic (cusped) electric field pattern, a small, spheroidal containment

zone, and is typically used as a precision measurement device.

The Penning-Malmberg trap, shown in Figure 3, is configured in a cylindrical shell design. The cloud forms an oblate spheroid (football shaped), and exhibits larger trap sizes with associated larger storage volumes.

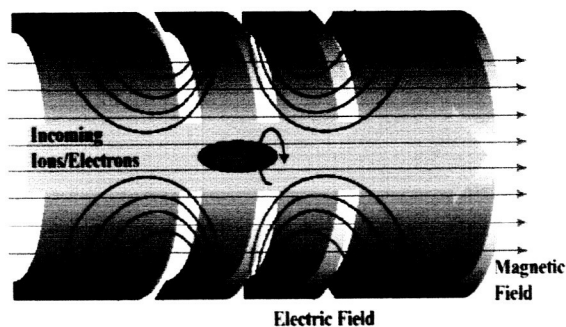


Figure 3. Penning-Malmberg Trap.

The High Performance Antiproton Trap (HiPAT) hardware, shown in Figure 4, uses a Penning-Malmberg layout and is designed for a capacity of 10^{12} antiprotons with a minimum storage lifetime of 18 days and is portable.

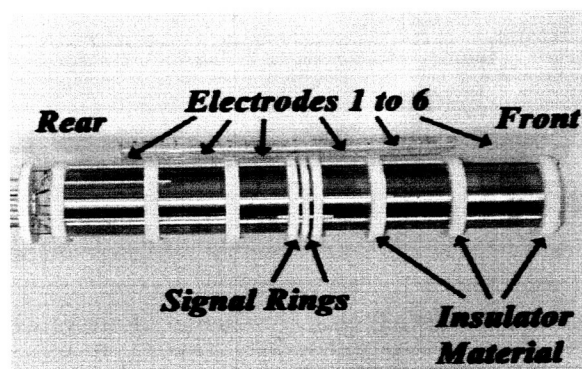


Figure 4. HiPAT Penning-Malmberg Trap.

The general features of the HiPAT trap include:

- A trapping region approximately 30-cm in length and 6-cm in diameter,
- A four Tesla magnetic field - by way of a superconductor magnet system,

- High voltage (25-kV) system, and
- A 10^{-11} Torr vacuum system.

Figure 5 shows how the high voltage system generates the antiproton containment zone.

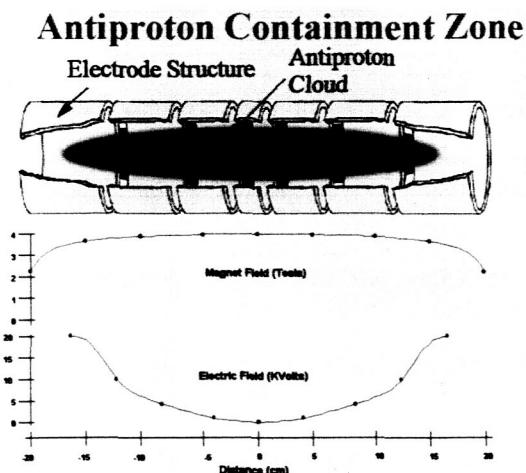


Figure 5. Antiproton Containment Zone.

Several fundamental motions (frequencies) of interest exist for ions trapped within the electromagnetic confinement region. They include axial, cyclotron, magnetron and other rotational frequencies.

The axial frequency characterizes an oscillation within the high electric fields, is a function of the mass of the antiproton, and is on the order of 2-MHz in frequency.

The cyclotron frequency is caused by the circular rotation of an ion around a magnetic field line (Lorentz force), is a function of the magnetic field, ion charge and mass, and is on the order of 60-MHz for this particular trap configuration.

The magnetron/rotational frequency is caused by the $\mathbf{E} \times \mathbf{B}$ rotational drift around the trap axis, and is on the order of 30-KHz to 30-MHz for this particular trap configuration.

The static confinement fields used within the typical Penning trap cannot contain an ion indefinitely due to loss factors – most significant are misalignment of \mathbf{E} and \mathbf{B} fields and particle diffusion. A process known as radio frequency stabilization provides the capability to reduce or eliminate diffusion and misalignment losses and also provides the required antiproton heating to minimize annihilation losses – this is accomplished by a rotating wall (or quadrupole

RF) in which selected frequency and amplitude adds energy to the system. As a result the ions are driven inward as energy is added to the system. Figure 6 shows both the rotating wall and quadrupole patterns.

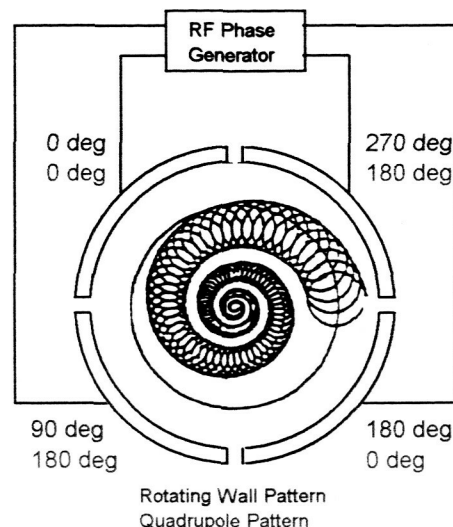


Figure 6. Rotating/Quadrupole Pattern.

The RF subsystem is comprised of an RF signal generator, a single 90-degree hybrid coupler, and two baluns. The signal is fed to the 90-degree hybrid coupler with the outputs then fed into two baluns to generate the required 0-, 90-, 180-, and 270-degree RF signals. The four outputs from the baluns are then fed into a -6-dB directional coupler to the wall of the vacuum chamber. Internal to the chamber the coaxial cables are replaced with twisted pair Kapton coated wire and then attached to the rings within the modified Penning-Malmberg trap. The -6-dB directional couplers are used to receive the signal emanating from the anti-proton cloud when it interacts with the transmitted signal. A simplified schematic is shown in Figure 7.

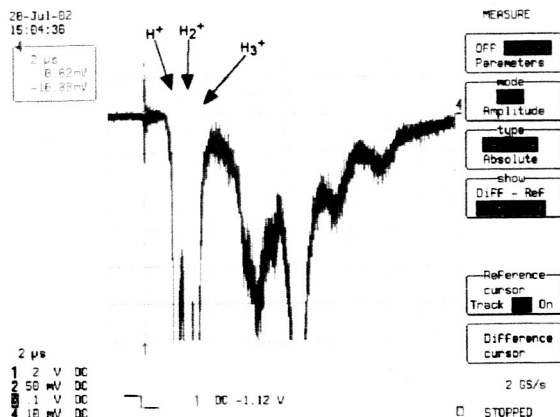


Figure 10. Trapping and Storage of H_x^+ ions within HiPAT.

The second injection of H_x^+ ion into HiPAT with a subsequent holding time with an injected swept RF signal (60.3-60.7 MHz) at +3-dBm is show in Figure 11.

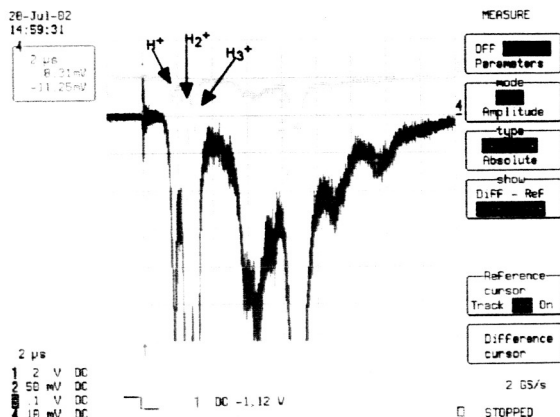


Figure 11. Trapping and Storage of H_x^+ ions within HiPAT with associated 60 MHz RF Drive.

As can be seen, the H^+ peak is now 0.05V, which is smaller than in Figure 10 showing that the H^+ ions were ejected from the trap.

The third injection of H_x^+ ion into HiPAT with a subsequent holding time and an injected swept RF signal (30-31 MHz) at +0-dBm is show in Figure 12. As can be seen the H_2^+ peak and to a lesser extent the H_3^+ peak have been reduced.

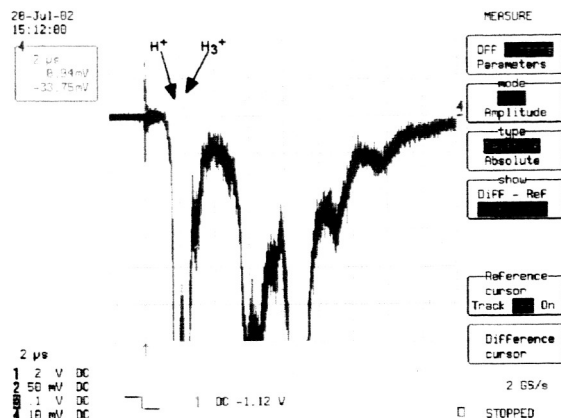


Figure 12. Trapping and Storage of H_x^+ ions within HiPAT with associated 30 MHz RF Drive.

The fourth and final injection of H_x^+ ion into HiPAT with a subsequent holding time and an injected swept RF signal (20-20.3 MHz) at +0-dBm is show in Figure 13. As can be seen the H_3^+ peak has been ejected from the trap.

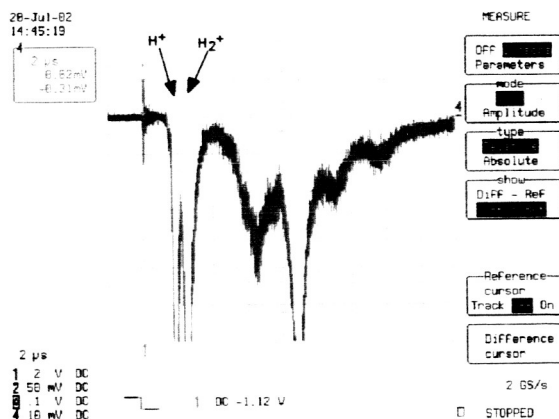


Figure 13. Trapping and Storage of H_x^+ ions within HiPAT with associated 20 MHz Drive.

The second means of validating the rotating wall methodology included the measurement of the mass of the electrons in H_3^+ ion clusters. The presentation of these results is given elsewhere and is beyond the scope of this paper. [1] Detailed laboratory results show, to within 7% of accepted theoretical

values, agreement between the expected and measured cyclotron resonance frequencies.

Recommendations

Overall, for a new design of a Penning-Malmberg trap, the outcomes were positive. In this paper, it was shown that the MSFC modified Penning-Malmberg trap produces excellent results. To further exploit these results, three recommendations for future work are offered.

The first recommendation is the need to increase the long-term storage capability of the trap, the idea that shows the most promise is the radio frequency stabilization.

The second recommendation is to increase the sensitivity of the overall system to detect the axial, cyclotron and magnetron/rotational frequencies. Special techniques had to be incorporated in the trap configuration to generate realizable results.

The third recommendation is for more work on the advancement of higher voltage traps. Currently, the internal components within the trap begin to break down at 10 kilovolts.

REFERENCES

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